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Factors contributing to the poor bulk behavior of meat and bone meal and methods for improving these behaviors ☆

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Abstract

Meat and bone meal (MBM), a product of the rendering industry, is a potential feedstock for numerous bio-based applications. Design of processing equipment for MBM is difficult due to MBM's bulk behaviors; it flows less easily than many other granular materials, and it tends to foul the surfaces of processing equipment. This study examines the major factors contributing to MBM's poor bulk behavior, including moisture content, fat content, particle size distribution and temperature, and the relative importance of these factors. Potential methods for improving MBM's bulk properties, including use of an anti-caking agent, dehydration, fat extraction, milling and refrigeration are also studied. The effects of these factors were determined by a standard laboratory measurement, the Hausner ratio, as well as by the rate of surface-fouling and dust generation using a pilot-scale aspirator. In contrast to past studies with other granular materials, moisture content was shown to have an insignificant effect on MBM's bulk behavior. The results, however, show that MBM fat content is a major determinant of the bulk behavior of the MBM. Reduction of fat content resulted in major changes in MBM's bulk behavior, by all measures used. Less dramatic changes were achieved through refrigeration to solidify the fat and/or treatment with an anti-caking agent.
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Keywords: Meat and bone meal; Powder; Cohesivity; Granular material; Hausner ratio; Aspirator; Anti-caking agent; Dust; Bulk density; Caking

1. Introduction

Meat and bone meal (MBM) is a commodity produced by the rendering of fat from unmarketable animal tissues. It comprises mainly chopped, dehydrated and partially defatted bones and offal (Garcia et al., 2006). Since the emergence of bovine spongiform encephalopathy, use of meat and bone meal in animal feed has been progressively restricted (Rodehutscord et al., 2002; Thiry et al., 2004). A looming glut of MBM has motivated efforts to develop new applications for MBM (Chaala and Roy, 2003; Conesa et al., 2003; Garcia et al., 2004; Park et al., 2000). MBM, however, can be challenging to process from a material handling perspective. It is a somewhat cohesive granular material. This cohesiveness complicates the design of equipment and processes to handle MBM. A recent study on air classification of MBM found that poor flow properties and surface-fouling were obstacles to the processing, storage and transport of MBM (Garcia et al., 2005). These problems necessitated equipment modification, use of processing equipment below its normal capacity, and a high proportion of downtime to clean fouled surfaces of the equipment.

The bulk behavior of granular materials, such as MBM, determines the special accommodations necessary to process them. The interrelated properties of bulk flow,

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fluidization behavior, and caking and dusting tendencies must be considered in the design of hoppers, conveyors, mixers, mills and other unit operations (Holdich, 2002). These properties depend on the intrinsic properties of the individual particles, and on their environment and history.

Other than properties intrinsic to the particles, moisture is most often cited as influencing the bulk behavior of a granular material. Increasing moisture content has been recognized to inhibit bulk flow and fluidization, reduce dustiness and promote caking (Pilpel, 1970; Plinke et al., 1994). These effects have been observed with a diverse range of materials including glass beads, titanium dioxide, sugar, flour and gypsum (Carr, 1970; Harnby et al., 1987; Plinke et al., 1994; Teunou et al., 1995). These effects all arise from increased inter-particle cohesion induced by moisture. Moisture can promote cohesion by multiple mechanisms, depending on the nature of the particle involved, and on the temperature, moisture and compaction applied to the particles over time (Adhikari et al., 2001; Ozkan et al., 2002).

Generally the flowability of a granular material improves with increasing particle size (Abdullah and Geldart, 1999; Teunou et al., 1995). For larger particles, the forces of gravity and inertia are large compared to the inter-particle forces, giving rise to low structural strength of the powder. Consequently, larger particles have an individual mobility that tends to result in "free flow" characteristics (Forsyth et al., 2002).

MBM is fairly fatty and has a slight, palpable greasiness or tackiness. Little information is available on the influence of fat content on the bulk behavior of granular materials. It has been found that increasing fat inhibits the release of airborne dust (Heber, 2002) and fat has been used effectively as an additive to reduce the dustiness of animal feed (Gore et al., 1986). One group (Wakiyama et al., 1992) found that fat content promoted caking of granular materials, especially when tested at temperatures above the melting point of the fat.

The present study identifies factors responsible for MBM's poor material handling properties, and evaluates potential treatments to improve these properties.

2. Methods

2.1. Sample preparation

Moyer Packing Co. (Souderton, PA) donated the MBM used in this study, which all came from a single manufacturing lot. Individual MBM particles vary widely in size and composition and the particle types have a strong tendency to spontaneously segregate, so care was required to obtain small, representative samples. A 20 kg sample of MBM was thoroughly homogenized and split into 600 g sub-samples by repeated cone and quartering. Except when noted otherwise, each sub-sample was conditioned for a minimum of four days prior to use by storing in a controlled temperature and relative humidity (RH) environment. An RH of 73.7% (±0.1, $n = 80$) was maintained using a standardized method (ASTM International, 2003) involving storage of the samples in glass desiccators over saturated solutions of sodium chloride. The samples were stirred daily to promote equilibration with the surrounding air, and the desiccators were stored in a 30 °C incubator (average $T = 30.6$ °C, ±0.03, $n = 80$). Preliminary experiments determined that this amount of incubation time was adequate for the MBM to equilibrate with the atmosphere surrounding it.

Samples treated with a temperature other than 30 °C were equilibrated at 30 °C as described above, and then hermetically sealed in a container with little headspace, and incubated at the final temperature. Milled samples were mixed approximately 1:1 with crushed dry ice, prior to being fed through a Wiley mill (Model 1, Arthur H. Thomas, Philadelphia, PA) fitted with a 1 mm outlet screen, and then equilibrated. Reduced fat MBM samples were produced by dehydrating MBM overnight and then extracting four times with hexane (1 mL/g MBM) and filtering through Whatman #1 (Whatman Inc., Florham Park, NJ) filter paper. The resulting MBM had a significantly reduced fat content (1.3% dry basis) compared to the unextracted MBM (9.1% dry basis). The anti-caking agents Zeofree 5162 (synthetic silicon dioxide) and Zeolex 7A (synthetic sodium aluminosilicate) were obtained from Huber Engineered Materials (Atlanta, GA).

2.2. Moisture adsorption isotherms

Samples of about 2 g MBM were dried in a 70 °C vacuum oven for 36 h and accurately weighed. Dry samples were sealed in chambers with constant relative humidity atmospheres. The equilibration chambers were set up according to ASTM E 104-02 (ASTM International, 2003) and consisted of small, hermetic boxes containing saturated salt solutions and a perforated plastic plate to suspend the sample above the salt solution. The solutions of LiCl, CH_3COOK, $MgCl_2$, K_2CO_3, NaBr, KI, NaCl, and KCl stored at 30 °C (±0.5 °C) equilibrate with the headspace air resulting in a RH of 11.3%, 21.6%, 32.4%, 43.2%, 56.0%, 67.9%, 75.1%, and 83.6%, respectively. The samples were removed from the chambers and weighed after incubating for 10–11 days (preliminary experiments determined the samples reached a constant mass after about four days). Moisture adsorption isotherms were determined in quadruplicate.

2.3. Bulk behavior testing

All testing was performed in a randomized order. The Hausner ratio is the ratio of a material's tapped bulk density to its loose bulk density (Grey and Beddow, 1969). Loose bulk density of each sample type was determined in triplicate using a standardized method (American Association of Cereal Chemists, 1995), slightly modified to work for MBM. Briefly, the hopper of a Winchester Bushel Weight Tester (Burrow's Equipment Co., Evanston, IL) is positioned over the center of a quart container, with the spout of the hopper exactly 2 in. above the top of the container. Test material flows through the hopper and overfills the container. The excess material is swept from the top of the container with a standardized 'stroker', in a standardized manner. If the method is followed exactly, the hopper becomes clogged with MBM. To avoid this, MBM was added to the hopper in two smaller batches. Tapped bulk density of each sample type was determined in at least triplicate using an Autotap (Quantachrome Instruments, Boynton Beach, FL) set to deliver 3000 taps to each sample.

Practical measurements of surface caking and dustiness were made by feeding the samples through a Kice Model 6DT4 Laboratory Aspirator Unit (Kice Industries, Wichita KS). Samples (650 g) were fed through the aspirator while it was operating at a pressure of −62 Pa. The aspirator is intended to classify materials into high and low terminal velocity fractions; when used to classify MBM, a significant portion of the original material does not get classified into either fraction. A portion passes through the system without being collected by the cyclone or the aspirator, but instead passes out with the exhaust air. The proportion of material that exits the aspirator in this manner was used as a practical indicator of the dustiness of the material. Another portion of the material does not exit the aspirator at all, but remains caked on the interior surfaces; the proportion of sample material that remained caked in the aspirator was used as a practical indicator of caking and surface-fouling. This method is non-standard and the results are only meaningful relative to one another.

Statistical comparison of result means consisted of ANOVA followed by computation of Fisher's least significant difference at $\alpha = 0.05$ (Montgomery, 2001). Because the replicates of loose and tapped bulk density are not paired, the standard deviation of the Hausner ratio was determined using the appropriate propagation of error formulas (Deming, 1943; Ku, 1966). Calculations were performed using Minitab release 14 (Minitab, Inc., State College, PA).

2.4. Thermal analysis

Test material was finely milled under liquid nitrogen and hermetically sealed in aluminum differential scanning calorimetry (DSC) pans. The thermal analysis was performed using a Pyris 1 DSC (Perkin–Elmer, Wellesley, MA). The initial scanning raised the specimen temperature from −20 to 60 °C at a rate of 10 °C/min, followed by cooling to −20 °C at 10 °C/min, a 2 min hold, and finally a second heating from −20 to 60 °C at a rate of 10 °C/min.

2.5. Other analysis

Particle size distribution and lipid content were determined according to ASTM D 1921-01 and ASTM D 3495-83, respectively (ASTM International, 1994; ASTM International, 2001). Moisture content determinations were performed according to ASAE S358.2, except that 2 g samples were used (American Society of Agricultural Engineers, 2003).

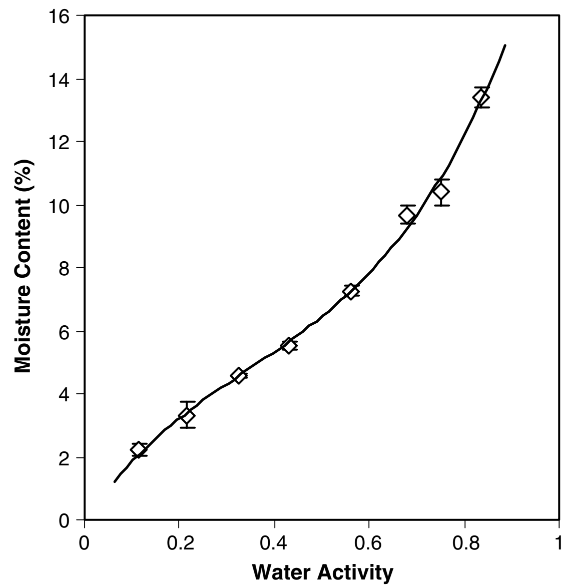

Fig. 1. Moisture adsorption isotherm for MBM at 30 °C. Error bars are present for each data point and represent ±1 standard deviation (s.d.).

3. Results and discussion

The moisture adsorption isotherm for MBM in Fig. 1 is a type II isotherm typical of biological materials (Bell and Labuza, 2000). MBM, however, is not particularly hygroscopic; at 30 °C and 50% RH, MBM equilibrates to 6.3% moisture (by interpolation). Under similar conditions, many biological materials adsorb more water; for example soy protein isolate and corn meal equilibrate to 11% and 11.5% moisture, respectively (Iglesias and Chirife, 1982).

The Hausner ratio (HR) was used to study the effect of moisture content on MBM's material handling properties. The HR has been repeatedly demonstrated as a reliable indicator of flowability and fluidization, using a wide variety of granular materials with a range of properties encompassing those found in MBM (Lindberg et al., 2004; Santomaso et al., 2003; Thalberg et al., 2004; Wong, 2000). It is sometimes interpreted as a metric of the friction condition in a moving mass stream (Grey and Beddow, 1969; Riley and Hausner, 1970). One study (Geldart et al., 1984) found that the Hausner ratio enabled one to distinguish quantitatively between the free-flowing, easy-to-fluidize group A and the cohesive, difficult-to-fluidize group C powders.

Drying of MBM does not increase its flowability (Fig. 2), as would be expected from past results, discussed in the previous section. The Hausner ratios of MBM equilibrated to 73.7% r.h. (8.6% moisture, wet basis) and partially dehydrated MBM (1.3% moisture, wet basis) were not significantly different. Granular materials with HR in the range of 1.25–1.4, such as these, are classified as difficult-to-fluidize

Group AC powders in Geldart's scheme (Geldart et al., 1984).

Fat content of the MBM, however, did show a highly significant impact on the behavior of MBM (Fig. 2). In these experiments, fat was extracted by a practical method, rather than an analytical method, so the reduced fat MBM had 1.31% lipid, d. b. (±0.5, $n = 2$), compared to the control material which had 9.05% lipid, d.b. (±0.1, $n = 2$). The average HR measured for the reduced fat material, 1.21, places it within Geldart's range for easy-to-fluidize materials (Geldart et al., 1984).

Milling of MBM resulted in a reduction in mean particle diameter (geometric mean weighted by particle mass) from 0.43 mm before milling to 0.34 mm after milling (Fig. 3). Additionally, the milling reduced the size distribution (geometric standard deviation of log-normal distribution by mass in base 10, dimensionless) from 0.39 to 0.23. Milling had no observable effect on HR (Fig. 2).

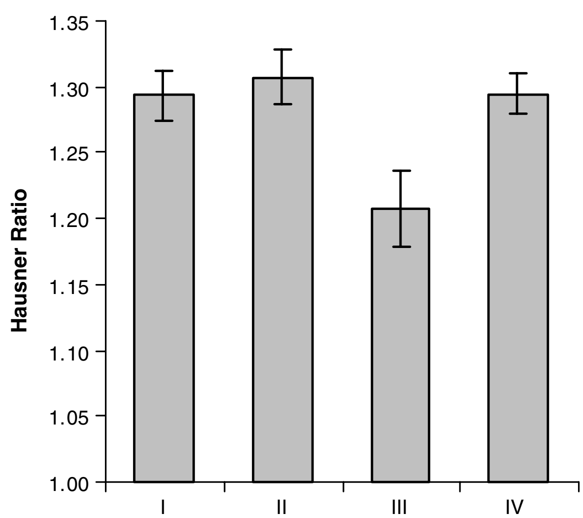

Fig. 2. Hausner ratio of MBM (I) as received, (II) reduced moisture, (III) reduced fat or (IV) milled ($n = 3$; error bars represent ±1 s.d.). Fisher's least significant difference at $\alpha = 0.05$ is 0.023.

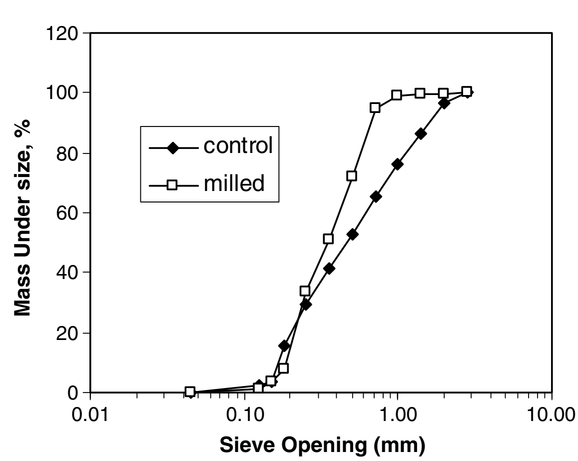

Fig. 3. Particle size distribution of MBM, as received and MBM that has been comminuted using a Wiley mill with a 1 mm screen.

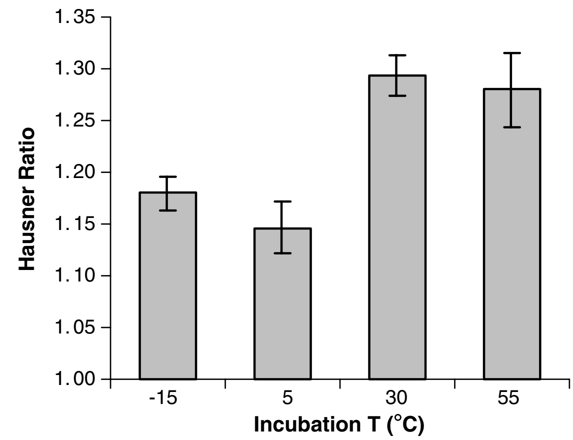

Fig. 4. Hausner ratio of MBM incubated at different temperatures ($n = 3$–5; error bars represent ±1 s.d.). Fisher's least significant difference at $\alpha = 0.05$ is 0.027.

Temperature had a large impact on the bulk behavior of MBM (Fig. 4). HR was much greater for 55 °C MBM compared to −15 °C MBM. A DSC thermogram of fat-free MBM is essentially featureless in the temperature range −20 to 55 °C (data not shown). It is notable that this thermogram does not contain any indication of a glass transition. In many past studies on food powders, the transition from a glassy to a rubbery state has been tied to increased cohesivity (Adhikari et al., 2001; Chuy and Labuza, 1994).

Fig. 5 is a thermogram of MBM that has had the signal from fat-free MBM subtracted, so that only the signal from the MBM fat remains. The crystallization behavior of fats, especially polydisperse fats such as the fat in MBM, is complex. In addition to the thermodynamically stable crystal form, fats can exist in a number of meta-stable crystal states, as well as mixtures of these states. Consequently, in most situations fats do not display a sharp transition from solid to liquid on the macroscopic scale. The thermogram in Fig. 5 demonstrates MBM fat crystallizing and melting in distinct stages. MBM fat heated from room temperature displays endothermic peaks centered at about 28 and 40 °C, indicating the melting of two types of fat crystal polymorphs. MBM fat cooled from room temperature exhibits an exotherm centered at around 5 °C, indicating either crystallization from the melt or transition of crystals from one polymorphic form to a more stable form.

Influence of temperature on MBM's bulk behavior corresponds well with the progressive state changes in MBM fat. At 55 °C MBM fat is completely liquid (National Renderers Association, 2003), and MBM is found to flow poorly at this temperature. With decreasing temperature, MBM fat is increasingly solid, and MBM is found to flow more readily.

These observations, however, appear to contradict the findings of Wakiyama et al. (1992). These investigators found that fatty powders had greater tendency to consolidate into cakes when stored at lower temperatures.

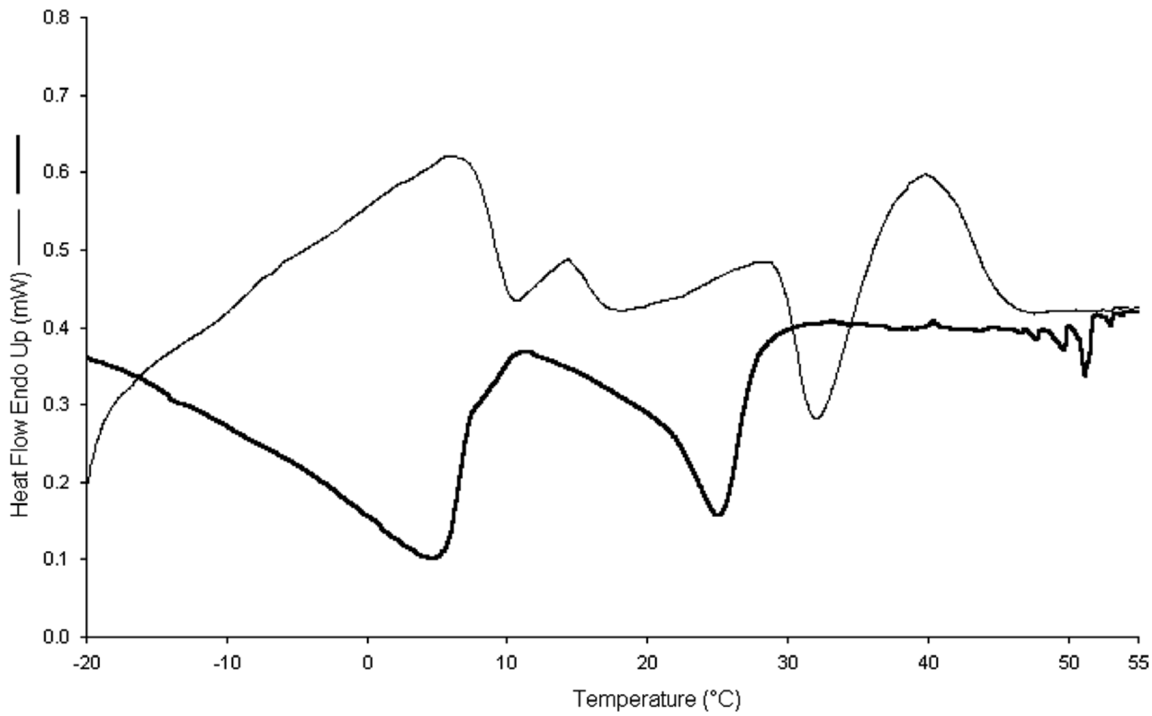

Fig. 5. Thermogram of MBM blanked against defatted MBM. Thin trace is heating, bold trace is cooling.

A large number of commercially available products are marketed as 'anti-caking agents' or 'glidants' (Anonymous, 1999). These substances can be added to granular materials in order to alleviate caking and improve free flow of the powder. While the mechanism of action of these substances is not completely understood, it is believed to involve a combination of factors including absorption of lipid and moisture, and reduction of contact between individual particles of the granular material. Recently, researchers using atomic force microscopy have shown that the glidant-induced decrease in angle of repose correlates well with decrease in adhesive bond between individual particles (Jonat et al., 2004).

When blended into MBM, the anti-caking agent Zeofree 5162 significantly reduced MBM's HR and AOR, when used at 1% or greater (Fig. 6). Zeofree 5162 has an oil absorption capacity of 220 mL/100 g. A similar anti-caking agent with less oil absorbing capacity (Zeolex 7A – 145 mL oil/100 g) was much less effective in overcoming MBM's cohesiveness.

While chilling, removing fat, and treatment with an anti-caking agent are each effective in improving the flowability MBM, these treatments only complement each other to a limited extent when used in combination (Fig. 7). In terms of Hausner ratio, only the combination of 2% Zeofree 5162 and chilling to −15 °C was more effective than any of the individual treatments.

In addition to difficulties in getting MBM to flow or fluidize, MBM can cause processing problems by caking on the surface of processing equipment. Fig. 8 demonstrates MBM progressively building up on the interior surfaces of an aspirator. This condition is undesirable for a variety of reasons including loss of materials, increase in drag and resistance to heat transfer across equipment surfaces, and potential to create a substrate for putrefying or pathogenic microorganisms.

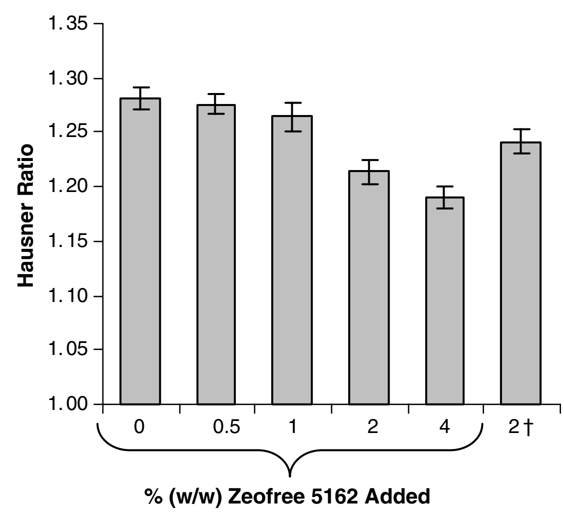

Fig. 6. Hausner ratio of MBM treated with anti-caking agents ($n = 3$; error bars represent ±1 s.d.). † Zeolex 7A used instead of Zeofree 5162. Fisher's least significant difference at $\alpha = 0.05$ is 0.011.

Some of the treatments used to improve flowability of MBM were also evaluated for their potential to limit caking (Fig. 9a). By either removing the majority of the MBM's fat or by chilling it and treating it with 2% (w/w) Zeofree 5162, the amount of caking was reduced dramatically. Aspirator build-up when processing reduced fat MBM was, on average, less than 10% of the build-up when processing normal MBM.

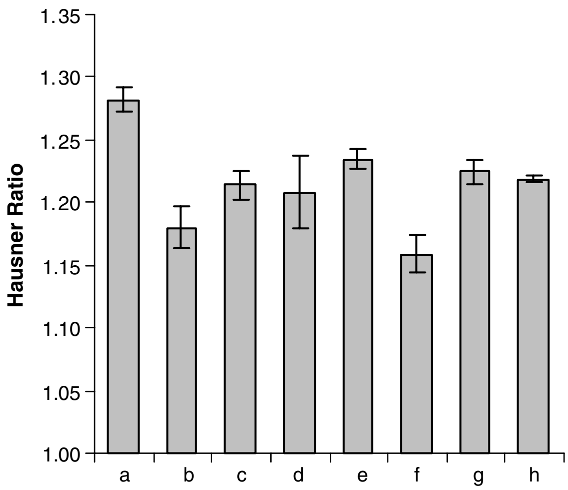

Fig. 7. Hausner ratio of MBM subjected to different treatments ($n = 3$; error bars represent ±1 s.d.): (a) control; (b) frozen; (c) 2% Zeofree; (d) reduced fat; (e) reduced fat and frozen; (f) 2% Zeofree and frozen; (g) 2% Zeofree and reduced fat; (h) 2% Zeofree and reduced fat and frozen. Fisher's least significant difference at $\alpha = 0.05$ is 0.015.

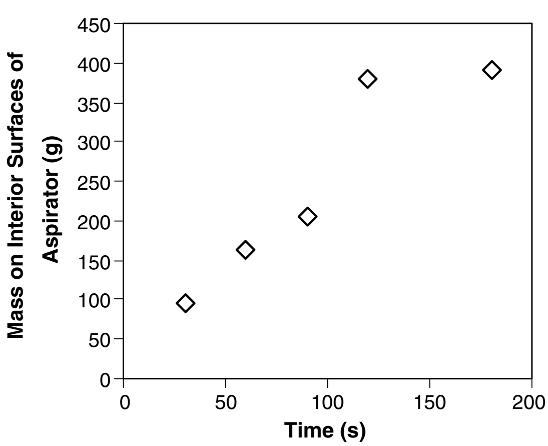

Fig. 8. MBM caked on the interior surfaces of aspirator after running different lengths of time.

These same treatments, however, resulted in an increase in the material's dustiness (Fig. 9b). Dustiness is important for occupational health, explosion risk and material loss (Holdich, 2002). Summing the proportions of the MBM that contributed to caking or dust with each treatment reveals that the reduced fat material had the smallest average proportion of the material (18.1 ± 5.6%) contributing to either surface-fouling or dust; the control and the frozen, 2% Zeofree 5162 treated MBM had 24.2 ± 4.1 and 24.0 ± 2.7, respectively.

4. Conclusions

The poor flow of MBM apparently results from a mechanism different than that described commonly for food powders (Boonyai et al., 2004). In the present work, fat content and the physical state of this fat were primary determinants of flowability. This understanding is critical to the

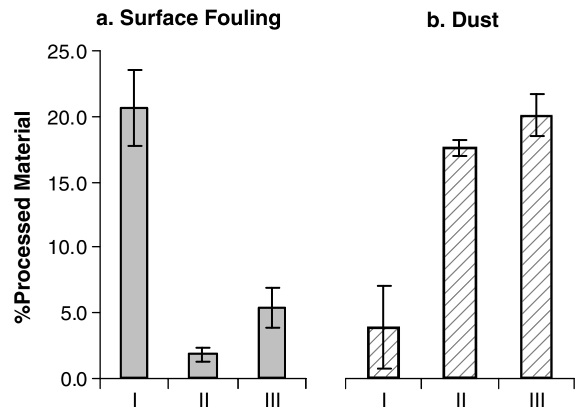

Fig. 9. Percentage of MBM that becomes (a) caked on the interior surfaces or (b) lost as dust when aspirating (I) MBM, as received, (II) reduced fat MBM or (III) MBM + 2% Zeofree 5162, incubated at −15 °C ($n = 3$; error bars represent ±1 s.d.).

design of solutions to overcome the problems caused by poor flow.

We suspect that the differences in temperature dependence between our observations and those of Wakiyama et al. show that fat induced caking is not an entirely generic phenomenon, but rather that the measurement of flowability should be well matched to the situation under investigation. The methods used by Wakiyama et al. may be superior when considering the cohesion of a granular material stored in a silo or hopper.

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